The Nesbitt group wants to figure out how chemistry works in outer space. In particular, the group wants to understand the "cosmo" chemistry leading to the generation of soot, which is similar to products of combustion here on Earth.

"Outer space is full of molecules," Nesbitt explains. "We want to discover how these molecules are formed out there." He adds that radio telescopes have gathered evidence of molecules made of long chains of carbon atoms. Some of these molecules are quite unusual and consist of dozens of six-carbon rings. Nesbitt wants to know how interstellar clouds end up with what are essentially pieces of tar in them. One clue has been the identification of ethynyl radical (C$_2$H) in the Orion Nebula (shown here) and several other interstellar gas clouds.

Ethynyl radical is a reactive chemical produced when acetylene (C$_2$H$_2$) burns. Almost as soon as a beaker of acetylene is lit, centimeter-long filaments made predominantly of carbon slowly rain down on the lab bench. What is amazing is that molecules containing two carbon atoms are producing a super molecule with a million billion carbon atoms in about a millionth of a second! The Nesbitt group thinks that ethynyl radical is key to understanding this transformation.

Once produced, ethynyl radical almost instantly reacts with other carbon-containing molecules to produce increasingly complex molecules, resulting in soot and ash. Since soot is also present in space, the challenge for the Nesbitt group is to understand both cosmo chemistry and combustion as well as explain their apparent similarities.

The Nesbitt group recently tackled this problem by investigating ethynyl radical with both a high-level theoretical analysis and high-resolution spectroscopy. In the experiment, former research associate Erin Sharp-Williams, graduate student Melanie Roberts, and Fellow David Nesbitt made ethynyl radical at high temperatures, then blew it out into a vacuum, where its temperature fell almost instantly from thousands of degrees Kelvin to about 10–15 K. Then, by carefully watching what happened, they were able to discern changes in the quantum states inside the ethynyl radical molecules. In this way, the group was able to obtain a more complete quantum fingerprint of this molecule than ever before — coming one step closer to understanding combustion and chemistry in the cosmos.

References

Physicists would very much like to understand the physics underlying high-temperature superconductors. Such an understanding may lead to the design of room temperature superconductors for use in highly efficient and much lower-cost transmission networks for electricity. A technological breakthrough like this would drastically reduce world energy costs. However, this breakthrough requires a detailed understanding of the physics of high-temperature superconductivity.

There is already a theoretical model, called the t-J model, that contains the ingredients needed to explain the basic physics underlying high-temperature superconductors containing copper and oxygen atoms. Unfortunately, because this model includes strong interactions of many electrons, it’s far too complex to solve with traditional analytical and computational methods. Without details from the model, it’s impossible to determine the relationship of experimental observations to it. Unfortunately, theorists have been stymied in their efforts to improve their understanding of high-temperature superconductivity — until now.

A powerful collaboration between researchers at JILA, Caltech, and Harvard has come up with an elegant way to sidestep the problem. Research associates Salvatore Manmana and Gang Chen and Fellows Deborah Jin and Jun Ye worked with Alexey Gorshkov of Caltech, Eugene Demler and Mikhail Lukin of Harvard to propose and develop a novel quantum simulator. The simulator uses a quantum gas of ultracold polar molecules of potassium-rubidium (KRb) created by Fellows Deborah Jin and Jun Ye. The ultracold molecules are polar because their electrons are unevenly distributed between the K and Rb atoms, creating an electrical asymmetry that makes them sensitive to electric fields.

The KRb molecules are located in an optical lattice, which forms a simulator. Optical lattices are crystals of light formed by intersecting laser beams. They make it possible to exactly control the quantum motions of atoms or molecules inside the simulator.

The behavior of the ultracold molecules in the new simulator will likely model that of high-temperature superconductivity in copper-containing wires because the simulator uses external electric fields to ensure that the KRb molecules obey the same t-J model that electrons obey in high-temperature superconductors. Therefore, when the experimentalists probe the behavior of the ultracold polar molecule system, they should gain insights into the fundamental physics of high-temperature superconductors.

In a study of conditions in the new simulator, the theorists demonstrated that the experimentalists should be able to adjust conditions in the simulator to enhance superfluidity, which is similar to superconductivity in solid materials. They also came up with some suggestions for studying quantum phase transitions in the simulator system, which is being explored by the Jin/Ye collaboration.

References:
Alexey Gorshkov, Salvatore R. Manmana, Gang Chen, Eugene Demler, Mikhail D. Lukin, and Ana Maria Rey, Physical Review A 84, 033619 (2011).

Ultrasound Polar Molecules to the Rescue!

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The Ye group has combined three experimental techniques to create a new cold molecule experiment for studying molecule collisions at a temperature of approximately 5 K.

Once the ND3 was flowing over the trapped OH, the experimentalists studied cold collisions between them. Because both OH and ND3 are dipolar molecules, they have an uneven internal distribution of electric charge resulting in one end being more positively charged, and the other end being more negatively charged. Cold dipole exhibits interactions that are small compared to similar molecules at room temperature, infrequent, and, until now, hard to measure. However, with the new setup, the Ye group was able to observe these characteristically subtle effects and manipulate them by adjusting external electric fields. The researchers observed that external electric fields increased the number of collisions between the dipolar molecules that result in OH molecules disappearing from the trap.

Their theorist colleagues were able to explain that two different kinds of collisions were responsible for this loss. A few OH molecules were knocked out of the trap by “elastic” collisions. Such collisions occur when two dipoles fly past one another, and each give each other a little kick. If the kick is hard enough, an OH molecule will fly right out of the trap. However, at temperatures of around 5 K, most elastic collisions aren’t hard enough to do this.

A second kind of collision, known as an inelastic collision, is actually responsible for most of the disappearance of OH molecules from the trap. This purely quantum mechanical interaction changes the quantum state of an OH molecule. Once this state change happens, the molecule simply falls out of the trap, since the trap only works on molecules in specific quantum states.

Clearly, there’s much more exciting physics to learn about the behavior of molecules inside the cold molecule experiment. That’s a good thing, too, because the cold molecule experiment is ideally suited for studying many of the molecules found on Earth and in space.

Reference:
Brian C. Sawyer, Benjamin K. Stuhl, Mark Ye, Timur Y. Tscherbul, Matthew T. Hummon, Yong Xia, Jacek Klos, David Patterson, John M. Doyle, and Jun Ye, Physical Chemistry Chemical Physics 13, 19059–19066 (2011).
When Becker and Takemoto were getting ready to send off an article on lasing, they had their doubts. The strange ionization behavior in the hydrogen molecular ion, $\text{H}_2^+$, had been observed in both theory and experiment, but the mechanism behind it was not clear. They were not sure if the molecule was really doing what they thought it was doing. 

The elucidation of the mechanism underlying the $\text{H}_3$ molecules’ flair for lasing was a coup for both the JILA theorists and the Berkeley experimentalists. Their article on this key accomplishment was selected as a 2010 “Editor’s Choice” by the Journal of Chemical Physics. 

References:

In laboratory experiments, excited $\text{H}_2$ molecules pile up until the lase energy by lasing at infrared wavelengths, creating $\text{H}_3$ molecules with lower energy. The electrons in these molecules are then able to interact with the $\text{H}_3$ ion core, which causes the molecule to fall apart.

Credit: Brad Baxley, JILA

A Flair for Lasing

Triatomic hydrogen ion ($\text{H}_3^+$) has many talents. In interstellar clouds, it can be blown apart by low-energy free electrons, which interact with the ion core ($\text{H}_3^+$), briefly forming unstable $\text{H}_2$ molecules. The interaction of the electron with the ion core almost immediately causes the molecule to fall apart into three hydrogen atoms ($\text{H}_3^+$) and an $\text{H}_2$ molecule. This reaction is known as dissociative recombination (see JILA Light & Matter, Spring 2006).

Back on Earth, $\text{H}_3^+$ will collide with free electrons and helium or neon in the laboratory to eventually form the same products. However, the laboratory reaction occurs in a series of steps inside an ionized gas (plasma). The Earthbound pathway to dissociation includes excited $\text{H}_2$ molecules lasing at infrared (IR) wavelengths to lose enough energy for the molecule to fall apart. Despite differing mechanisms, $\text{H}_3^+$ dissociation on Earth and in outer space does have one thing in common: The Greene theory group at JILA has explained them both.

Recently, graduate student Jia Wang and Fellow Chris Greene worked with experimentalists at the University of California, Berkeley, (1) to explain what is being done inside the plasma and why, and (2) to elucidate a complex dissociation pathway involving interactions of $\text{H}_3^+$ ions, free electrons, $\text{H}_2$ molecules, and helium atoms ($\text{He}_2$) inside a supersonically expanding plasma. In 2007, the experimentalists found the lasing spectrum in the lab and determined it could only be due to $\text{H}_3$ molecules. Greene, who was on sabbatical at Berkeley at the time, and Wang calculated more than 20 different lasing line frequencies for the $\text{H}_3$ molecule. Their theoretical frequencies corresponded reasonably well to the ones measured experimentally.

Since then, Greene and Wang have worked with the experimentalists at Berkeley to come up with an explanation of the behavior of the $\text{H}_3$ molecules in the lab experiment: The researchers found that $\text{H}_3$ molecules are created in collisions of $\text{H}_3^+$ ions with free electrons in the plasma. But, unlike $\text{H}_3$ molecules formed in space, these molecules don’t immediately fall apart. When an $\text{H}_3$ molecule is formed inside a plasma in the laboratory, the captured electron can collide with a helium atom and gain angular momentum, which makes it harder for the electron to interact with the ion core. Consequently, highly excited $\text{H}_3$ molecules inside the plasma will cascade through states of decreasing energy by spontaneously losing energy. The $\text{H}_3$ molecules eventually reach a quasi-stable state in which collisions with He no longer lower their energy and they accumulate inside the plasma. Eventually, these $\text{H}_3$ molecules will lase at infrared frequencies. The lasing process transfers the $\text{H}_3$ molecules to a state in which their electrons are traveling slowly enough to interact with their ion cores. As soon as this interaction occurs, the molecule falls apart into either three H atoms or an H atom and an $\text{H}_2$ molecule.

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Credit: Brad Baxley, JILA

Quantum Body Swapping

“THERE’S SOMETHING HAPPENIN’ HERE, WHAT IT IS AIN’T EXACTLY CLEAR.” —BURLINGTON HEPWORTH

Theorists Norio Takemoto (now at the Weizmann Institute of Science) and Fellow Andreas Becker figured that something was amiss when they first analyzed the details of what occurs when Earth and in outer space does have one thing in common: The Greene theory group at JILA has explained them both.

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Graduate student Jennifer Lubbeck (Jimenez Group) spent the summer of 2011 doing research in the Molecular Spectroscopy Laboratory at the RIKEN Institute in Wako, Japan. Her host group included 16 postdocs and four graduate students. The group was under the direction of Chief Scientist Taie Tahara. However, Lubbeck actually worked directly with just five other young scientists under the supervision of Professor Kunihiko Ishii (Ish-san).

“I was able to learn ultrafast techniques there that aren’t in use here at JILA,” Lubbeck says. “The experience helped me become a more well-rounded biophysics researcher.”

Lubbeck’s project was the study of the response of red fluorescent proteins to ultrafast laser light. Red fluorescent proteins are derived from sea anemones and coral. They have a barrel-shaped symmetric structure that surrounds and protects a color-producing entity (chromophore) that fluoresces red. Because developing a more stable red fluorescent protein is her thesis work, it was able to overnight samples from the Jimenez lab to RIKEN for use in her summer project.

At RIKEN, I primarily used spectroscopy to see which areas of the protein moved the most when the chromophore was excited by the laser,” Lubbeck said. “I was especially interested in finding out if some red fluorescent proteins were more flexible than others, because increased flexibility of the part of the protein where the chromophore could indicate a structural weakness.” In the process of learning to make careful measurements of time-dependent protein spectra, Lubbeck was also able to introduce some biophysics techniques to her lab mates.

“It was a good exchange,” Lubbeck reflects now on her 10-week summer program, which began with a week of orientation at the Sodenkai Institute in Hayama, Kanagawa prefecture. Her orientation included classes in Japanese language, musical instruments, and tea ceremony.

At the end of orientation, she stayed with a local family, who introduced her to Karaoke and took her to see the sights of Kamakura. After leaving “early” at 6:00 a.m. one day to climb Mt. Fuji, for instance, the bus got to the Mt. Fuji trailhead around 8:30 p.m. She hiked all night, arriving at the summit in time for the sunrise and misty views. Then she hiked back down the mountain, caught the bus back to Wako, arriving at her apartments at noon. After sleeping until the next morning, she went back to work for a regular 15-hour day.

“The experience was very good,” she says now. “I had the opportunity to see a hierarchical lab structure and learn how Japanese scientists run a laboratory. For instance, my boss Ishi-san decided everyday which one of us would get to see the next day’s data. The labs at JILA have a much flatter structure.”

Back at JILA, Lubbeck is hard at work analyzing data from the summer research program. Her expenses for the program were paid by a grant from the U.S. National Science Foundation, with a contribution from the Japan Society for the Promotion of Science.

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Graduate student Jennifer Lubbeck (left) of the Jimenez Group spent the summer of 2011 doing research in the Molecular Spectroscopy Laboratory at the RIKEN Institute in Wako, Japan. She worked under Professor Kunihiko Ishii (Ish-san). Credit: The RIKEN Institute

For instance, there are four pieces of circumstantial evidence that the blue suprergiant was undergoing a core merger of two stars when it blew up. First, the cylindrical symmetry of the explosion illuminated in the center of a recent Hubble Space Telescope picture, shown here, suggests the presence of two stellar cores. Second, there are two outer rings beyond the one that is brightly illuminated in the picture. These rings strongly resemble the planetary nebulae surrounding binary star systems. Third, because a second star isn’t anywhere to be found, it must have merged with the blue suprergiant. Finally, the blue suprergiant stars typically don’t go supernovae. Ordinarily, huge red suprergiant stars, which are as big as our solar system, are the stars that explode. However, the merger of two stellar cores would be capable of causing a relatively small blue suprergiant star to explode.

The two-center merger theory also explains a key step in the evolution of the star that exploded. About 20,000 years before the supernova, a red suprergiant star (formed when the two stars initially began to merge) shed a dense outer layer and became a smaller blue suprergiant star. About ten years after the supernova, a ring composed of the ejected outer layer of the star began to light up. Hot spots developed when the supernova shockwave began to enter the ring and ionize it. These spots emit light blue and red “supercontinuum” spectra, as shown here.

Evidence supporting these theories about the evolution and explosion of the star has been available for some time. However, recent ultraviolet and x-ray images are adding new information about the blue suprergiant star that exploded.

For instance, the newly refurbished Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope began sending ultraviolet (UV) spectra of the debris cloud and the circumstellar ring in 2010 after a hiatus of more than six years. In comparison with two Hubble mission line scans made by the main stellar ingredient of the ionizing gas, the hydrogen, the researchers discovered that one of them, called Lyman-alpha, is produced primarily in the ring’s hot spots and scattered toward the observer by collisions with hydrogen atoms in the debris. The other, called H-alpha, comes from hydrogen atoms in the debris entering shocked gas near the rings.

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The Secret of the Resonant Lattice

Theoretical physicists recently combined two powerful tools for exploring ultracold atomic gases: optical lattices and Feshbach resonances. Optical lattices are crystals of light formed by interfering laser beams. Feshbach resonances in an ultracold atom gas occur at a particular magnetic field strength and cause ultracold atoms to form very large, loosely associated molecules. However, because lattice atoms interact strongly at a Feshbach resonance, the physics of Feshbach resonances in an optical lattice is quite complicated. Fortunately, a recent analysis of the behavior of two single atoms in a resonant lattice has led to a powerful new mathematical model capable of shedding light on the fundamental physics of the quantum behavior of these systems.

The creators of the new model included senior research associate Javier von Stecher, Fellow Ana Maria Rey, and their colleagues Victor Gurarie and Leo Radzihovsky from the University of Colorado. Von Stecher and his colleagues found that atoms in an optical lattice couldn’t move at all. At a Feshbach resonance, the atoms made up of two atoms in different energy bands. Rather, they looked at the molecule as if it were a new particle that could only move in its own energy bands. These molecular bands were different from those of the atoms.

There were as many molecular energy bands as atomic bands. But, there was a key difference: A molecular band would move in response to changes in the magnetic field. The atomic bands would not.

Tuning the magnetic field turned out to be the control knob for making things really interesting in a resonant lattice. As a molecule band moved in response to changes in the magnetic field, it inevitably ran into a new, kind of lattice Feshbach resonance appeared. This resonance created a new intriguing coupling mechanism for the two atoms that could take place as a molecule band interacted with an atom band.

During this interaction, the molecule band became distorted. Several things could then happen. If the molecule was not moving, it wouldn’t even “see” or interact with the atoms it was passing by. However, if the molecule was moving (even just a little bit), it would “see” the atoms around it. This kind of molecule could break apart into atoms, remain as a molecule, or give rise to another new molecule. In fact, the real quantum state of the molecule under the influence of the Feshbach resonance was not any of these possibilities; rather it was a superposition of all of them at the same time.

The new Feshbach resonance is not only fascinating, but also has given von Stecher and his colleagues the key to creating a new and simpler mathematical model that will be capable of describing a more complicated system with many particles. Because the new model makes a complex system easier to understand, it will help researchers better understand the physics of very complex systems such as liquids and solids.

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Reference:
Sculpting a Star System: The Inner Planets

The Solar System has a remarkable number of planets. It includes four rocky planets (Mercury, Venus, Earth, and Mars), four giant gaseous planets, and countless smaller worlds. Early on, there may even have been a fifth rocky planet that collided with the Earth, forming the Moon. We owe the survival of so many terrestrial planets (and our own evolution as a species) to the relatively stable orbits of Jupiter, Saturn, Uranus, and Neptune during the 100 million years it took to form the inner planets of the Solar System.

Most extrasolar planetary systems may not have been so fortunate. They show signs of being survivors of violent instabilities that knocked at least one giant planet completely out of the system. The worst instabilities would have resulted in the destruction of all the system’s rocky planets. Some “milder” instabilities left a single rocky planet intact, but badly shaken up. The survival of two or more rocky planets like those in our Solar System requires a stable set of giant gas and ice planets. And, theoretical calculations suggest that such stability may be relatively uncommon.

Only 15–25% of planetary systems around Sun-like stars end up with three or four terrestrial planets, according to a recent simulation by Fellow Phil Armitage and his colleagues at the University of Bordeaux, Princeton University, Cambridge University, and the University of Bordeaux, Princeton University, Cambridge University. The simulations showed that the planets’ sizes tell us something important about the Solar System’s unique history. Armitage says, “About 700 million years after the birth of the Solar System, Uranus and Neptune moved far enough away from Jupiter and Saturn to interact with the then much-larger Kuiper belt. This interaction brought Uranus and Neptune into their present orbits. It also destabilized countless planetesimals, hurling many into outer space and others straight into the heart of the Solar System. This bombardment was responsible for some of the craters still visible today on the Moon. It must have inflicted even more damage on the Earth and Mars, and on the moons of the giant planets.

Despite the scars we see today, the bombardment came much too late to significantly affect the evolution of our Solar System’s inner planets. Fortunately for us, they remained stable. However, there is evidence that the bombardment increased the amount of dust in the outer regions of both Earth and Venus. On Earth, lulls in the rain of impacting comets and asteroids may even have allowed some primitive life forms to survive.

Reference:
Long long ago galaxies now far away formed around ravenous black holes scattered throughout the Universe. Some 12.5 billion years later, JILA scientist Gayler Harford and Fellow Andrew Hamilton have identified the superhighways that funneled gas into some of the nascent galaxies. These thruways not only routed gas to feed the monster black holes, but also supplied raw materials for the billions and billions of stars that have illuminated those galaxies ever since.

The cosmic gas-transporting superhighways were filaments of ordinary matter that extended outwards from primordial galaxies and often linked entire strings of galaxies, according to simulations performed by Nick Gnedin of Fermilab and analyzed by Harford. Under favorable conditions in the simulation, the filaments formed long cylinders of gas at uniform temperatures, typically 10,000 to 20,000 K. The simulations suggest that the properties of the gas entrained in the filaments are far more important in determining filament structure than any nearby dark matter.

Haloes of dark matter surround most galaxies. Scientists have long thought dark matter’s role to be so critical to galaxy formation that the structure and behavior of nearby gas clouds could be ignored in models of galaxy formation. However, Harford’s results suggest that the gas hitchhiking along the filaments into the core of galaxies may be more important than dark matter in determining whether an emerging galaxy can pull in enough gas to form stars.

Many of the galaxies analyzed by Harford do not have intergalactic filaments attached to them. Such galaxies may be unable to accumulate enough gas to form stars. Harford says that there may be a new class of galaxies in the Universe that have not been detected because they are not luminous.

There may even be some of these dark galaxies near our own Milky Way. The standard model of cosmology predicts many more satellite galaxy haloes around the Milky Way than the galaxies we see. According to Harford, the galaxies may well be there. We just can’t see them.

Reference: